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DEVELOPMENT OF SUPERHEATING POWER REACTORS OF BELOYARSK NUCLEAR POWER STATION (БАЭС) TYPE

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Introduction

Ever increasing needs for electric power promote the power engineering growth, for this, the construction of installations with a high unit output being more profitable.

At present in the USSR turbine sets for various steam conditions are being built and designed (Table I).

Table 1

Steam Conditions and Output of Turbine Sets Currently Built and Designed in the U.S.S.R.

Steam conditions before turbine		Electric output, Mw
pressure, atm.	temperature, °C	
90	535	100
130	565/565	150, 200
240	580/565	300, 500, 800, 1000

As can be seen from Table 1, the increase in turbine set output is associated with the increase in temperature and pressure

of steam in use.

Progress in nuclear power development, as well as in conventional power engineering, is based on construction of nuclear power plants with a high unit output. Furthermore, it is preferable to install high quality steam power reactors. This makes it possible to use high power turbine sets and to have high efficiency of the nuclear power plant operation.

Uranium-graphite tube type superheating reactors similar to those of the Beloyarsk nuclear power station (БАЭС) meet the requirements mentioned above completely. A tube type reactor is in successful operation at the First Soviet atomic power station (1). As to the first reactor of Beloyarsk, transition to operation at rated power is studied and the second reactor is in the stage of mounting. The first reactor design was described in a paper submitted to the Second Geneva Conference (2), its start-up and pilot operation are described in a paper submitted to this conference (3). The БАЭС reactors produce steam at 90 atm. and 500°C.

Various design developments show that transition from high steam conditions directly to supercritical parameters with coolant once-through circuit is more preferable way of developing the reactor under consideration. And alternatively, as will be shown later, it is less desirable to use 130 atm. turbine sets with intermediate steam superheating.

Technological Flowsheet Development

The choice of a proper flowsheet is of importance when constructing high power plants. In choosing the design of a nuclear power plant as in choosing that of a conventional power plant, such factors as reliability, simplicity and economics should be the main considerations. In addition, fluid-tight circuits and water conditions for nuclear power plant should meet especial requirements.

The proper choice of a flowsheet together with construction problems solution concerning the channel thermal operation conditions enables the reactor power to be considerably increased

without enlarging the reactor over-all dimensions, as is the case with the БАЭС second reactor, where the power was increased twice as many, compared to that of the first reactor.

Several possible flowsheets for uranium-graphite tube type reactors are shown in Fig.1.

The 100 Mwe БАЭС first reactor is shown in Fig.1a.

Figures 1б and 1в show the БАЭС second reactor with steam washing and without it. These flowsheets being somewhat changed in channel construction permitted to raise the reactor electric output up to 200 Mw. Figs. 1г, 1д, 1e and 1ж, show possible designs of a supercritical reactor, which allows to raise its output to 800-1000 Mw. These are considered below in detial.

It is quite natural that once-through tube reactor system is much simpler and less expensive than indirect cycle system with its additional bulky and expensive heat exchangers, separators, circulation pumps, fittings and pipes as well as higher coolant conditions. When using nuclear superheating system and especially once-through-tube type systems radiation safety of the plant serviced rooms, turbine set in particular, is considerably dependent upon the reactor design. In this connection, the advantages of the БАЭС reactors should be mentioned.

Dose rate in the serviced rooms where primary coolant equipment is present, for the reactors of this type is determined by coolant salt and oxygen activity only, as tubular fuel element construction prevents from fission fragments leakage into the coolant in case of operation with defective fuel elements. Experiments carried out at the First Soviet atomic power station showed that from the radioactivity point of view, nuclear superheated steam may be used provided good water purity in the separators and proper steam separation (4). The БАЭС first reactor meets these requirements. In the second reactor, due to water multiple circulation, salt activity build-up and its subsequent transport by steam to superheating channels and turbine is possible. For this reason, in the second reactor careful purification from salts and corrosion products is provided, that is, ion-exchange filters are installed after the turbine condenser; water blowing from steam separators is intensified; feed water quality and condenser grid plates tightness is to meet more severe requirements.

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All mentioned above is still more necessary to provide for once-through tube reactor system.

Increase in reactor output over 200-300 Mw with overall dimensions preserved and superheated steam pressure 90 to 100 atm is not economically attractive, as in this case one should have the alternative of giving up the more suitable operation of one reactor with one turbine (or at least with two) or using a turbine with intermediate steam superheating. The plant layout and maintenance become more complex, besides, pipe length is increaded, additional heat exchangers have to be used, steam separation cost is raised, and multiple circulation curcuit resistance is increased. The enlargement of intermediate superheaters surface results both in rise of their cost and in increase in corrosion products amount in the circuit, thus the plant water conditions being worsened.

The reactor output can be considerably increased when transition to supercritical steam is made. In this case the plant flowsheet is substantially simplified, as there is no need for a circuit with coolant multiple circulation, circulation pumps and separators. When using supercritical coolant, burnout and hydrodynamic instability in fuel channels are eliminated.

One of possible designs of supercritical nuclear power plant is shown in Fig.1Г. Feed water is transported from the deaerator to the channels of the first group where superheated steam is produced. One part of this steam is fed to the external intermediate superheater, and the other passes through a throttle device to the main steampipe and then to the turbine. Supercritical pressure steam is fed from the intermediate superheater to the reactor fuel channels, of the second group, where it is heated up to a predetermined temperature and also goes to the turbine. To make the plant operation more reliable at transients, a temperature regulator is installed behind the intermediate superheater on the side of heating steam.

The power plant design similar to that under consideration, but without high pressure heaters, which can be excluded to reduce the amount of corrosion products in the circuit, is shown in Fig. 1Д.

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Without high pressure regeneration the plant efficiency is lowered by 1.5% as compared with the design shown in Fig.1r but in this case the plant water conditions are found to be considerably improved.

The plant design with the turbine having double intermediate steam superheating is shown in Fig.1e. The need for superheated steam throttling after the channels of the first group is eliminated. All steam passes from intermediate superheaters to the channels of the second group and then to the turbine.

A most promising is a supercritical once-through tube reactor system with one group of fuel channels and without intermediate steam superheating (Fig.1ж). The turbine set used consists of three stages: the first one uses supercritical steam, two others operate on saturated steam. To remove moisture from the steam at the low pressure cylinder inlet it is necessary to have a separator.

The possibility of further development is not limited of course to the nuclear power plant designs with supercritical uranium-graphite tube type reactors considered above. Plant economic characteristics, and firstly, the estimated cost per kilowatt are affected by the unit power rise and proper choice of a flowsheet. The reactor power output is directly dependent upon operating conditions of evaporating and superheating channels, this is considered below.

Evaporating Channels Operating Conditions

Fail-safe operation of evaporating channels can be achieved under conditions of absence of critical heat fluxes in fuel elements and of coolant flowrate pulsations between and inside the channels. In designing the БАЭС first reactor several experiments have been carried out to study water boiling conditions in small diameter tubes (2).

For the second БАЭС reactor in connection with its output rise, the inner diameter of the fuel element tubes was increased from 8.2 up to 10.8 mm and as a result, an additional experiment on burnout heat fluxes in small diameter tubes was required.

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The experiments were carried out in an electrically heated installation on tubes 10.4 mm i.d. and 3.8 m long. The dependence of steam voids upon mass flow rate for various heat fluxes under the conditions of burnout heat flux at a pressure of 150 atm. is shown in Fig.2. During experiments the burnout was determined by step increase in tube wall temperature.

The investigations made at different pressures and identical thermal loads, steam voids and coolant mass flow rates showed that the lower coolant pressure, the higher wall temperature under burnout heat flux. At the same time, it was found that with decreasing coolant pressure, the burnout heat flux void increases.

In addition, the installation with electrically heated channel modulating the БАЭС reactor flowsheet was used to study hydrodynamic stability of coolant flow rate along parallel channel tubes under boiling conditions at pressure of 20-150atm, flow rate of 500-5000 kg/hr and channel power of 50-800 kw.

During experiments flow rate pulsations were found to exist at small (up to 5 wt.-%) and large (over 40 wt.-%) steam voids. In the last case pulsations ceased with increase in flow rate or pressure. Thus, at coolant flow rate of about 1500 kg/hr, pressure of about 40 atm and output of 400 kw flow rate pulsations occurred at steam void of about 40 wt.-% and at pressure of 60 atm, the other conditions being the same, they occured at steam void 80 wt.-%.

As experiments showed, flow rate pulsations at high steam void are not dangerous for the БАЭС type reactors, as the nominal pressure in the evaporating circuit is notless than 50 atm, steam void at channel outlet being not greater than 35 wt.-%.

In Fig.3 the experimental curves obtained in the installation are shown, and represent the boundary between hydrodynamically stable region of flow rates in the channels and a region of pulsations occurred in the evaporating channels at low coolant steam void. The curves are plotted as coolant flow rate versus pressure at various outputs of evaporating channels. The curves shown in Fig.4, also determine the regions of stable and unstable flow rates in the channels but here as coolant flow rate versus

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steam void at the channel outlet when channel power changes from 50 to 800 kw. It was found that curve positions practically do not depend upon coolant pressure. Stable channel flow rate regions, Figs.3 and 4, are above the corresponding curves for the evaporating channel. As can be seen from Figs.3 and 4, with increase in the channel power stable flow rate region decreases.

When the flow rate pulsations are present in the channels, the tube temperature oscillates the oscillation frequency coinciding with the flow rate pulsations. When the pressure rises, amplitude of temperature oscillations and coolant flow rate pulsations decreased. Just the same result was observed when thermal load is decreased or when the coolant flow rate through the channel is increased. Thus, at coolant pressure of 50 atm and channel power of 200 kw the temperature oscillation amplitude is 65°C at flow rate of 1000 kg/hr, and only 30°C at flow rate of 1500 kg/hr.

The experimental determination of burnout heat flux and flow rate pulsation conditions enable the БАЭС 2 reactor evaporating channels to be chosen correctly as far as their operating conditions and their possibilities are concerned. In this reactor, coolant flow rates are distributed in such a way as to provide identical burnout safety margin for the most dangerous channel section taking into consideration the steam void and thermal load changes over the channel length rather than to be proportional to channel power. This coolant flow rate distribution makes it possible to increase somewhat the average steam void at the reactor outlet. Thus, at 27 wt.-% steam void at the outlet of the most loaded central evaporating channels, the steam void at the peripheral channels outlet can be increased up to 35%, this gives the average steam void at the reactor outlet 31%.

The БАЭС second reactor evaporating channels consist of fuel element tubes with a larger diameter than that in the first reactor to reduce thermal loads and circuit flow friction. Evaporating fuel elements of the БАЭС first reactor have the inner tube of 9.4 x 0.6 mm and the second reactor elements have 12 x 0.6 mm tube, the outer diameter of 20 mm being the same. In the second reactor channels the diameter of the central tube

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with coolant is also somewhat increased. As to the rest, the design of the БАЭС first and second reactor evaporating channels is identical. As fuel in the evaporating channels of both reactors U-Mo alloy is used with Mg as a filler to make a thermal contact. The characteristics of the evaporating channels are presented in Table II.

Table II

Evaporating Channels Characteristics

	First Atomic Power Station Reactor	БАЭС I reactor	БАЭС 2 reactor				
			zone I	zone II	zone III	zone IV	zone V
Channel power, kw	300	405	771	634	617	545	517
Coolant flow rate through the channel, kg/hr	2500	2400	5500	4700	4150	3550	3250
Steam void at channel outlet, %	-	33.6	27.6	29.3	30.5	32.1	34.2
Pressure at channel inlet, atm	100	155	-	-	155	-	-
Pressure at channel outlet, atm	98	150			145		
Coolant temperature at channel inlet, °C	200	300			303		
Coolant temperature at channel outlet, °C	290	335			338		
Maximum thermal load (kcal/m2hr).10^6	1.8	0.5	0.8	0.7	0.6	0.5	0.5
Circulation rate m/sec	4	3.5	4.6	4.0	3.5	3.0	2.7
Maximum temperature, °C; tube inner wall	324	355			365		
fuel	382	400			415		
Burnout heat flux / Max. heat flux		2	1.85	1.9	1.9	2.0	1.95

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Superheating Channels Operation Conditions

Superheating channels of nuclear superheat reactors are the most loaded parts of the reactor structure as they operate at higher temperature then evaporating channels. High operating temperatures of superheating channels limit the choice of nuclear fuel and structural materials.

The design of the БАЭС superheating channels somewhat differs from evaporating channel design, although the fuel elements are there of the same size as in the evaporating channels. According to the initial design of superheating channels steam went through the channel central tube and its superheating was fulfilled when it went through six fuel elements. Then a U-shaped design of superheating channels was developed (Fig.5). The distinctive feature of the design is that it steam is superheated there in succession: first when it moves through three fuel elements downwards and then when it goes upwards through the following three fuel elements. The U-shaped design of channels differentiates temperature operating conditions of upstream and downstream fuel elements, and this makes it possible to use more simple and less expensive evaporating channel elements as downstream elements. U-shaped design with successive superheating enables also the temperature of the reactor graphite stack to be lowered. Thus, the transition from the initial design of superheating channels to a U-shaped design lowers the graphite stack temperature by about 100% (at channel power of 360 kw.) Graphite temperature is lowered due to removal of heat generated in the graphite stack by U-shaped channel downstream fuel elements having relatively low temperature. Graphite temperature decrease favourably affects the graphite operating conditions and reactor physical characteristics, the latter being somewhat improved with decreasing in neutron gas temperature. At last, using U-shaped superheating channels the central tube is eliminated, as a result, the amount of steel is reduced in the reactor core. Fine-control pin is installed in place of the central tube, which enables fuel channels power to be flattened to some extent.

Upstream superheating elements design and dioxide uranium-based fuel ensure steam superheating up to 500°C, this is

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confirmned by loop-tests on the first power plant reactor (4).

The БАЭС superheating channels characteristics are listed in Table III.

Table III

Superheating Channels characteristics

	БАЭС I reactor	БАЭС 2 reactor	
		downstream fuel elements	upstream fuel elements
Maximum channel power, kw	368	767	
Minimum channel power, kw	202	548	
Steam flow rate through maximum power channel, kg/hr	1900	3600	
Steam flow rate through minimum power channel, kg/hr	1040	2570	
Channel inlet pressure, atm	110	132	124
Channel outlet pressure, atm	100	125	110
Channel inlet steam temperature, ^{o}C	316	328	397
Channel outlet steam temperature, ^{o}C	510	399	508
Maximum thermal load K/cal/m^{2}hr.10^{-6}	0.48	0.82	0.68
Maximum steam velocity, m/sec	57	76	112
Maximum temperature, ^{o}C:			
tube inner wall	530	426	531
fuel	550	482	565
graphite	725	735	

U-shaped superheating channel is a variant of multipass channel where the coolant passes a number of fuel elements in succession. Coolant passage in succession ensures different temperature operating conditions for fuel elements and makes it possible to some extent to change these by a proper choice of power of fuel elements operating in series. Thus, for a multipass channel a number of more important and complex fuel elements located only at the coolant outlet leg is greatly reduced. As to

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the rest regions of coolant passage, more simple and less expensive elements can be used. The advantages of multipass channels can be more clearly seen while using supercritical once-through system.

Locations of fuel Channels in the Reactor Core

The use of evaporating and superheating channels operating under different temperature conditions is associated with the problem of their proper distribution in the reactor core. The most suitable for start-up and shut-down cooling conditions is a mixed distribution of different channels, as it ensures heat transfer from superheating to evaporating channels, this facilitating the both channel operation conditions at both regimes mentioned. The location of superheating channels at the periphery of the core increases the member of the channels, but pressure losses in the steam pass are reduced. Temperature operating conditions of fuel elements and graphite stack are almost not affected by the channel location. Thus, when superheating channels of the БАЭС 1 reactor were located in the centre or at the core periphery maximum temperature of the fuel elements differed only by 20°C, and graphite stack maximum temperature differed by 60°C.

In the БАЭС 2 reactor superheating channels are located in the centre in rows (Fig.6), this, together with fine regulation pins contributes to flattening of energy release distribution over the reactor radius. Non-uniformity of energy release distribution over the second reactor radius is reduced to 1.3, while at the first reactor it amounts to 1.4. Thermal neutron distribution which defines energy release over the second reactor radius and is rather equal to that which exists at the end of the core life to fuel burn-up non-uniformity, is shown in Fig.7. Thermal neutron distribution over the БАЭС 2 reactor height is shown in Fig.8. The distribution distortion with core life is due to nonuniform uranium burn-up.

Supercritical once-through tube reactors, where all the channels operate under similar conditions, energy release distribution required can be achieved by a suitable distribution of

control rods and burnable poison.

Conclusion

Some possibilities of development of uranium-graphite nuclear superheat reactors of the БАЭС type are considered. Transition from the dual cycle design of the БАЭС 1 reactor to a direct cycle design and some modification in fuel channel construction made it possible to uncrease the БАЭС 2 reactor power up to 200 Mw (5). Much greater progress can be achieved with this type of reactors while using supercritical coolant. In this case heat exchange and flow hydrodynamics are considerably improved, this together with once through system enables the reactor net power output to be increased to 800-1000 Mw, practically with the same core dimensions, as those of the БАЭС reactors. With once-through system the advantages of multipass fuel channels mentioned above can be revealed more clearly both from the view.point of graphite stack and fuel element.temperature operating conditions and a relatively small amount of structural materials in the core. Calculations show that uranium enrichment of 5% can provide a burn-up equivalent to power production of 40000--45000 Mwd/ton of U.

Increase in reactor unit power overall efficiency and uranium burn-up greatly improve the nuclear plant economic characteristics, both [illegible] the estimated kilowatt and electric power production cost.

It is easy to change the core composition in uranium-graphite tube type reactors due to removable fuel channels. This enables to use modified fuel channels and fuel elements in reactor subsequent reloadings, particularly, to use structural materials with low cross-section and fuel compositions with low non-productive neutron absorption.

As the reactor core is in hermetically sealed vessel, it is possible not to use fuel element antifragmentary cladding, this, on the one hand, makes it possible to remove gas fission products from the core and, on the other hand, substantially reduces (approximately by 30%) the amount of steel in the core. It is

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evident that this modification will greatly improve neutron balance and other reactor characteristics.

Power of uranium-graphite tube type reactors can be increased without any limitations. Thus, with increase in the core diameter by 35-40% reactor net output can be raised to 1500 Mw.

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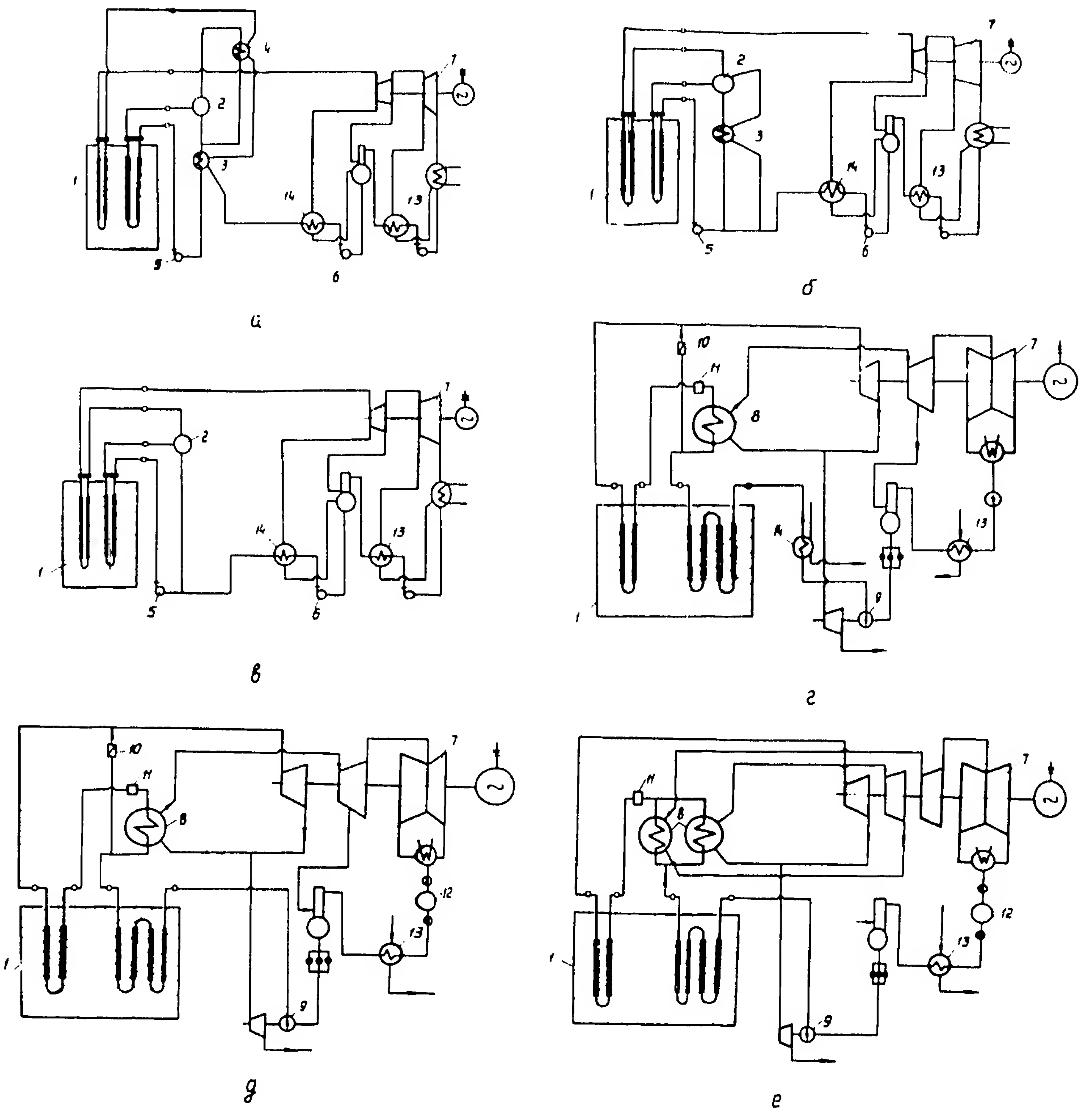


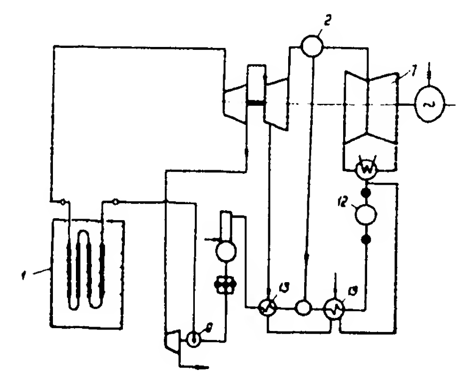


Fig. 1. Possible flowsheets for uranium-graphite tube type nuclear superheat reactors.
1 - reactor, 2 - separator, 3 - steam generator heater, 4 - steam generator evaporator, 5 - circulation pump, 6 - feed pump, 7 - turbine, 8 - intermediate superheater, 9 - feed pump, 10 - throttle device, 11 - water injection, 12 - condensate purification, 13, 14 - low and high pressure regenerative heaters.

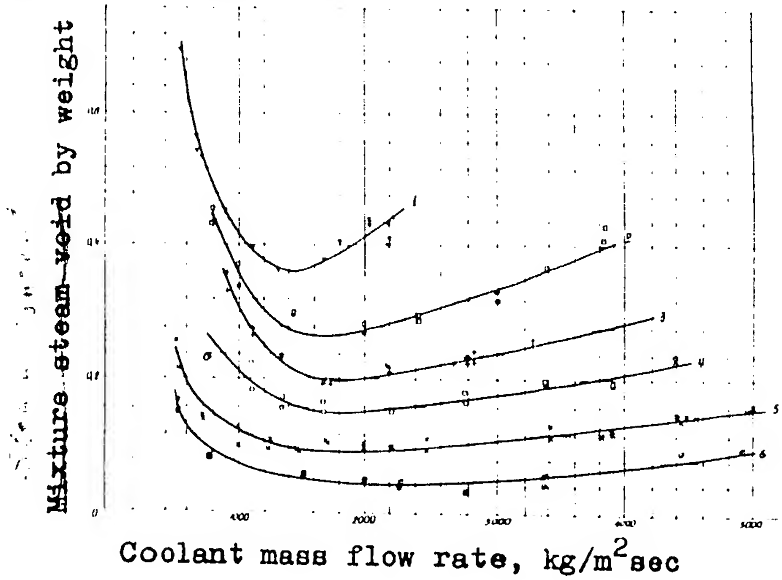


Fig. 2. Burnout heat flux steam voids (by wt.) versus mass flow rate at constant specific thermal load P = 150 atm, d_{in} = 10.4 mm: 1 - $q=0.31.10^6$; 2 - $q=0.45.10^6$; 3 - $q=0.64.10^6$; 4 - $q=0.94.10^6$; 5 - $q=1.28.10^6$; 6 - $q=1.62.10^6$ $Kcal/m^2hr$.

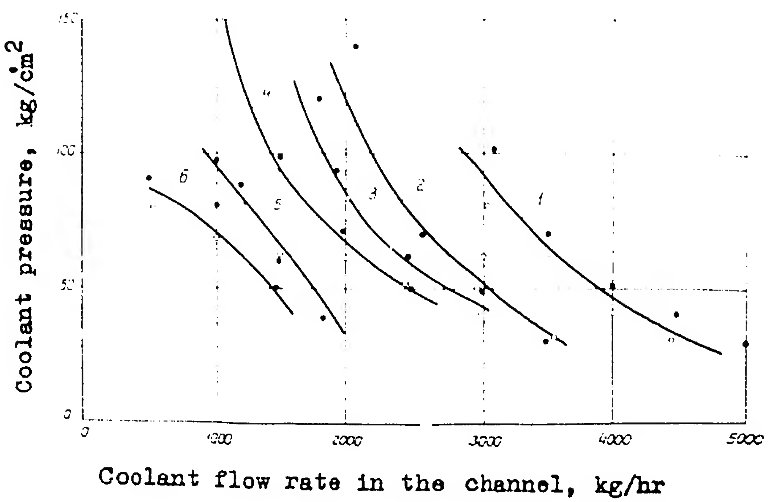


Fig. 3. Channel coolant pressure versus coolant flow rate at the channel power: 1 - 800 kw, 2 - 400 kw, 3 - 300kw, 4 - 200 kw, 5 - 1000 kw, 6 - 50 kw. Curves represent the boundaries between hydrodynamically stable and unstable flow rates. Blackened points correspond to conditions without pulsations.

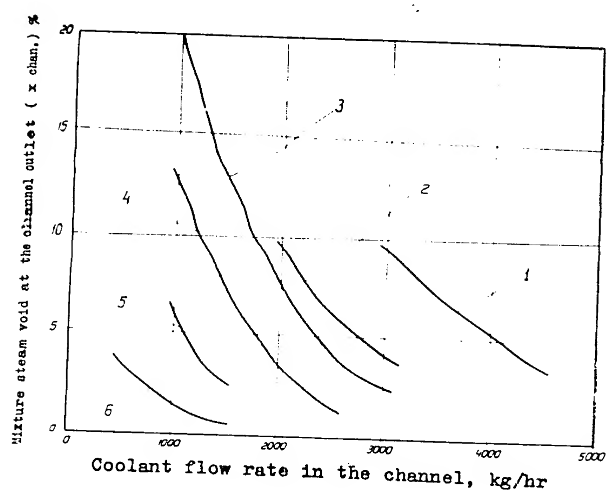
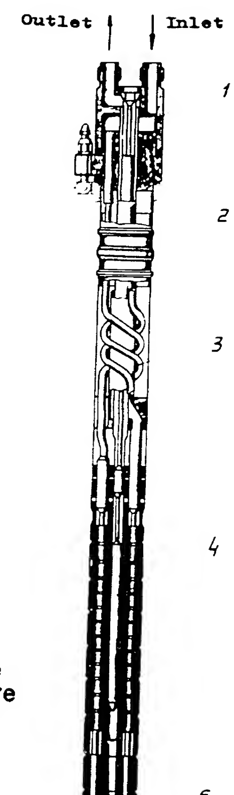


Fig.4. Channel steam voids (by wt.) versus coolant flow rate at the channel power: 1 - 800 kw, 2 - 400kw, 3 - 300kw, 4 - 200kw, 5 - 100kw, 6 -50kw. Averaged curves representing the boundaries of stable and unstable flow rates. The region of stable flow rates through the channel tubes is located above the corresponding curves. (The curves are plotted on the basis of experimental results for steam voids corresponding to conditions without pulsation at different coolant pressures and flow rates).



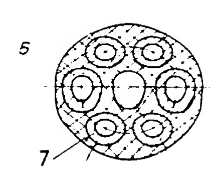


Fig.5. U-shaped superheating channel
1 - upper end cap,
2 - packing rings,
3 - temperature compensator,
4 - absorber pin,
5 - lower end cap,
6 - upstream fuel element,
7 - downstream fuel element.

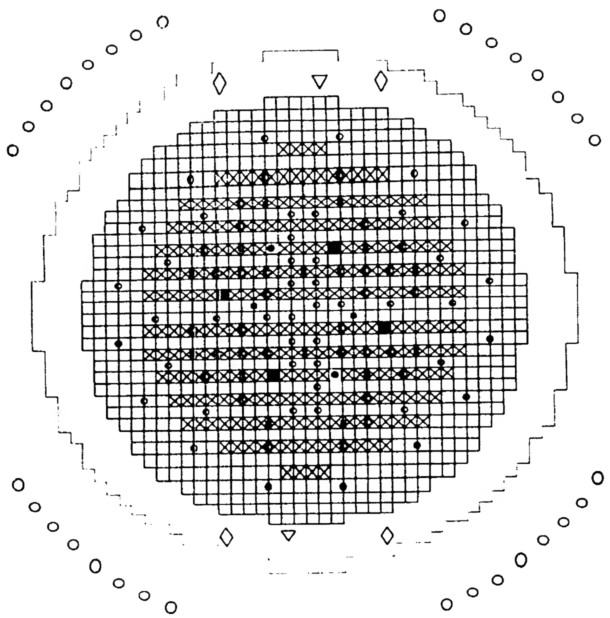


Fig.6. Locations of Channels in the Core.

			Number
□	evaporating fuel channels	-	732
⊠	superheating fuel channels	-	266
◐	shim rod channels	-	80
■	scram rod channels	-	16
■	automatic-control rod channels	-	4
▽	counting chamber channels	-	2
◇	starting chamber channels	-	4
○	ionization chamber channels	-	30

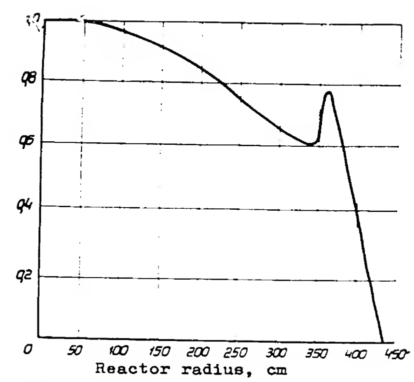


Fig.7. Thermal neutron distribution over the reactor radius.

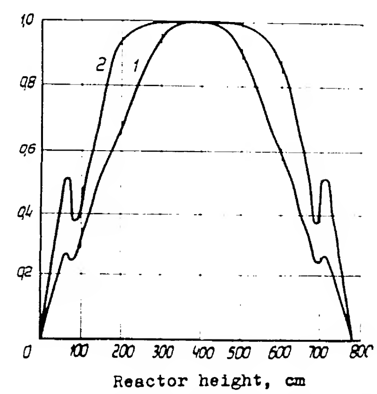


Fig.8. Thermal neutron distribution over the reactor height:
1 - at the beginning of the core lifetime
2 - at the end of the core lifetime.

Figures to paper "Development of Superheating Power Reactors of Beloyarsk Nuclear Power Station (БАЭС) Type"

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Fig. 3. Channel coolant pressure versus coolant flow rate at the channel power: 1 - 800 kw, 2 - 400 kw, 3 - 300 kw, 4 - 200 kw, 5 - 1000 kw, 6 - 50 kw. Curves represent the boundaries between hydrodynamically stable and unstable flow rates. Blackened points correspond to conditions without pulsations.

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Fig. 5. U-shaped superheating channel.

1 - upper end cap, 2 - packing rings, 3 - temperature compensator, 4 - absorber pin, 5 - lower end cap, 6 - upstream fuel element, 7 - downstream fuel element.

Fig. 6. Locations of Channels in the core.

		Number
□	- evaporating fuel channels	- 732
⊠	- superheating fuel channels	- 266

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◐ - shim rod channels - 80

■ - scram rod channels - 16

■ - automatic-control rod channels - 4

▽ - counting chamber channels - 2

◊ - starting chamber channels - 4

○ - ionization chamber channels - 30

Fig. 7. Thermal neutron distribution over the reactor radius.

Fig. 8. Thermal neutron distribution over the reactor height.

1 - at the beginning of the core lifetime,

2 - at the end of the core lifetime.

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